

Indirect Signatures of Type I See-Saw Scenarios

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Abstract. We consider the low energy constraints that can be applied to type I see-saw extensions of the Standard Model in which the right-handed neutrinos are taken at the electroweak scale. In the reported scenarios, the flavour structure of the charged current and neutral current weak interactions of the Standard Model leptons with the heavy right-handed neutrinos is essentially determined by the neutrino oscillation parameters. In this case, correlations among different measurable phenomena in the lepton sector may provide compelling indirect evidence of low energy see-saw mechanism of neutrino mass generation.

1. Introduction

The measurement of the solar and atmospheric neutrino oscillation parameters has provided compelling evidence for physics beyond the Standard Model (SM) of elementary particles. Massive active neutrinos can be naturally accounted for in see-saw type extensions of the SM, where new fermion and/or scalar representations are introduced in the theory with suitable Yukawa couplings to the SM lepton doublets [1]. The mass of the new physical states is in general unrelated to the electroweak (EW) symmetry breaking scale and, therefore, can assume arbitrary large values up to the Planck scale.

On the purely phenomenological side, it is interesting to study see-saw scenarios in which new physics is manifest at the TeV scale and can be probed in collider searches, LHC included. In this physical context, the phenomenology of type I see-saw extensions has been studied in detail in [2, 3], in a model independent way. The new particle states in such scenarios consist of at least two heavy SM-singlet fermions, which are conventionally denoted as right-handed (RH) neutrinos, ν_{aR} ($a > 2$), and give rise, when EW symmetry is broken, to the following mass terms in the Lagrangian

$$\mathcal{L}_\nu = -\overline{\nu_{\ell L}}(M_D)_{\ell a}\nu_{aR} - \frac{1}{2}\overline{\nu_{aL}^C}(M_N)_{ab}\nu_{bR} + \text{h.c.}, \quad (1)$$

where $\nu_{aL}^C \equiv C\overline{\nu_{aR}}^T$ ($a = 1, 2, \dots, K$), $M_N = (M_N)^T$ is the $K \times K$ Majorana mass matrix of the RH neutrinos and M_D provides the $3 \times K$ neutrino Dirac mass term. The Majorana mass m_ν for the active left-handed neutrinos is given by the well known see-saw relation: $m_\nu \cong -M_D M_N^{-1} (M_D)^T$. After the diagonalization of the full mass matrix given in (1), the charged current (CC) and neutral current (NC) weak interactions involving the heavy Majorana

mass eigenstates N_j ($j = 1, 2, \dots, K$) can be expressed as [2]:

$$\mathcal{L}_{CC}^N = -\frac{g}{2\sqrt{2}} \bar{\ell} \gamma_\alpha (RV)_{\ell k} (1 - \gamma_5) N_k W^\alpha + \text{h.c.}, \quad (2)$$

$$\mathcal{L}_{NC}^N = -\frac{g}{2c_w} \bar{\nu}_{\ell L} \gamma_\alpha (RV)_{\ell k} N_{kL} Z^\alpha + \text{h.c.}, \quad (3)$$

with $R^* \cong M_D M_N^{-1}$ at leading order in the see-saw expansion and $V^T M_N V \cong \text{diag}(M_1, M_2, \dots, M_K)$. The couplings $|(RV)_{\ell j}|$ can in principle be sizable, typically $|(RV)_{\ell j}| \sim 10^{-(3 \div 2)}$ for $M_k \approx (100 \div 1000)$ GeV. Then, in order to reproduce small neutrino masses via the see-saw mechanism, a “large” contribution to m_ν from N_1 is *exactly* cancelled by a negative contribution from a second RH neutrino, say N_2 , provided:

$$(RV)_{\ell 2} = \pm i (RV)_{\ell 1} \sqrt{\frac{M_1}{M_2}}, \quad (4)$$

where $M_{1,2}$ is the mass of the RH neutrino $N_{1,2}$. Barring accidental cancellations, relation (4) is naturally fulfilled in models where an approximately conserved lepton charge exists. In such scenarios N_1 and N_2 form a pseudo-Dirac pair and the neutrino oscillation parameters fix the flavour structure of their weak CC and NC couplings to gauge bosons and charged leptons, up to an overall constant y (see [2, 3] for details):

$$|(RV)_{\ell 1}|^2 = \frac{1}{2} \frac{y^2 v^2}{M_1^2} \frac{m_3}{m_2 + m_3} \left| U_{\ell 3} + i \sqrt{m_2/m_3} U_{\ell 2} \right|^2, \quad \text{NH}, \quad (5)$$

$$|(RV)_{\ell 1}|^2 = \frac{1}{2} \frac{y^2 v^2}{M_1^2} \frac{m_2}{m_1 + m_2} \left| U_{\ell 2} + i \sqrt{m_1/m_2} U_{\ell 1} \right|^2 \cong \frac{1}{4} \frac{y^2 v^2}{M_1^2} |U_{\ell 2} + i U_{\ell 1}|^2, \quad \text{IH}, \quad (6)$$

where m_1, m_2 and m_3 are the light active neutrino masses in the case of a normal/inverted hierarchical (NH/IH) mass spectrum.

2. Neutrinoless double beta decay in low scale see-saw scenarios

The mass splitting of the two RH neutrinos is highly constrained from the experimental upper limits set in neutrinoless double beta $((\beta\beta)_{0\nu})$ decay experiments. Indeed, in this case the effective Majorana mass $|\langle m \rangle|$, which controls the $(\beta\beta)_{0\nu}$ -decay rate, receives an additional contribution from the exchange of the heavy Majorana neutrinos N_k , which may be sizable/dominant for “large” couplings $(RV)_{\ell j}$. For $K = 2$, given a nucleus (A, Z) , one has (see [2, 3] for details):

$$|\langle m \rangle| \cong \left| \sum_{i=1}^3 U_{ei}^2 m_i - \sum_{k=1}^2 F(A, M_k) (RV)_{e1}^2 M_k \right|, \quad (7)$$

where for $M_k = (100 \div 1000)$ GeV: $F(A, M_k) \cong (M_a/M_k)^2 f(A)$, $M_a \approx 0.9$ GeV and $f(A) \approx 10^{-(2 \div 1)}$. Using eq. (4), the N_k contribution to the effective Majorana mass is simply

$$\langle m \rangle^N \cong -\frac{2z + z^2}{(1 + z)^2} (RV)_{e1}^2 \frac{M_a^2}{M_1} f(A), \quad (8)$$

with $z \equiv |M_2 - M_1|/M_1$. In the case of *sizable* couplings of RH neutrinos to the charged leptons, e.g. $|(RV)_{\ell 1}| \approx 10^{-2}$, this contribution can be even as large as $|\langle m \rangle^N| \sim 0.2$ (0.3) eV for $z \cong 10^{-3}$ (10^{-2}) and $M_1 \cong 100$ (1000) GeV [2, 3].¹ An effective Majorana mass of this order

¹ Therefore, in this scenario the two RH neutrinos N_1 and N_2 form a pseudo-Dirac pair. Notice that this conclusion is valid even in the case in which there is no conserved lepton charge in the limit of zero splitting at tree level between the masses of the pair [2, 3].

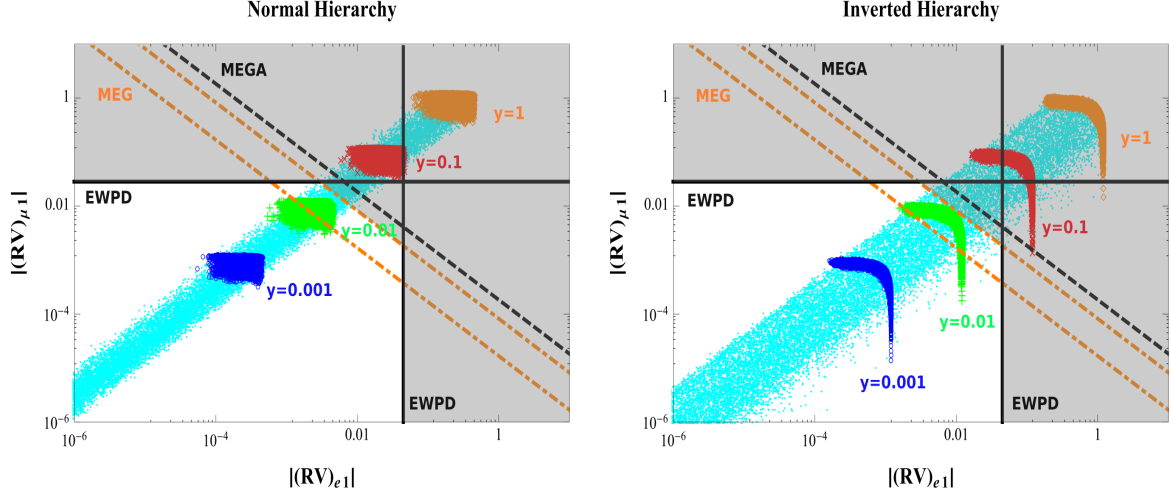


Figure 1. Correlation between $|(RV)_{e1}|$ and $|(RV)_{\mu 1}|$ in the case of NH (left panel) and IH (right panel) light neutrino mass spectrum, for $M_1 = 100$ GeV and fixed values of y . The cyan points correspond to random values of $y \leq 1$.

of magnitude may take place in both types of neutrino mass spectrum and can be accessible in ongoing experiments looking for $(\beta\beta)_{0\nu}$ -decay (*e.g.* the GERDA experiment [4], which can probe values of $|\langle m \rangle|$ up to ~ 0.03 eV).

3. Charged lepton radiative decays in low scale see-saw scenarios

In the scenario under discussion, lepton flavour radiative decays allow to put further constraints on the size of the mixing between light and heavy Majorana neutrinos. The strongest bounds are obtained from the current upper limit on $\mu \rightarrow e + \gamma$ branching ratio [3]:

$$B(\mu \rightarrow e + \gamma) = \frac{\Gamma(\mu \rightarrow e + \gamma)}{\Gamma(\mu \rightarrow e + \nu_\mu + \bar{\nu}_e)} = \frac{3\alpha_{\text{em}}}{32\pi} |T|^2, \quad (9)$$

$$T = \sum_{j=1}^3 [(1 + \eta) U]_{\mu j}^* [(1 + \eta) U]_{ej} G\left(\frac{m_j^2}{M_W^2}\right) + \sum_{k=1}^2 (RV)_{\mu k}^* (RV)_{ek} G\left(\frac{M_k^2}{M_W^2}\right) \\ \cong 2 [(RV)_{\mu 1}^* (RV)_{e1}] [G(M_1^2/M_W^2) - G(0)], \quad (10)$$

where $\eta \equiv -RR^\dagger/2$. The last relation arises from (4) and taking into account that $z \ll 1$, because of $|\langle m \rangle|$ upper limit. Therefore, taking $B(\mu \rightarrow e + \gamma) < 2.4 \times 10^{-12}$ at 90% C.L. from MEG experiment [5], the following constraint for $M_1 = 100$ GeV ($M_1 = 1$ TeV) is derived [3]

$$|(RV)_{\mu 1}^* (RV)_{e1}| < 0.8 \times 10^{-4} (0.3 \times 10^{-4}). \quad (11)$$

This can be recast as an upper bound on the neutrino Yukawa parameter y (see figure 1) [3]:

$$y \lesssim 0.036 (0.09) \text{ for NH with } M_1 = 100 \text{ GeV and } \sin \theta_{13} = 0 (0.2), \quad (12)$$

$$y \lesssim 0.030 (0.16) \text{ for IH with } M_1 = 100 \text{ GeV and } \sin \theta_{13} = 0 (0.2). \quad (13)$$

4. Interplay between lepton flavour and lepton number violating observables

Since the flavour structure of the neutrino Yukawa couplings is fixed in the present scenarios, correlations among different low energy leptonic observables may be a relevant signature of

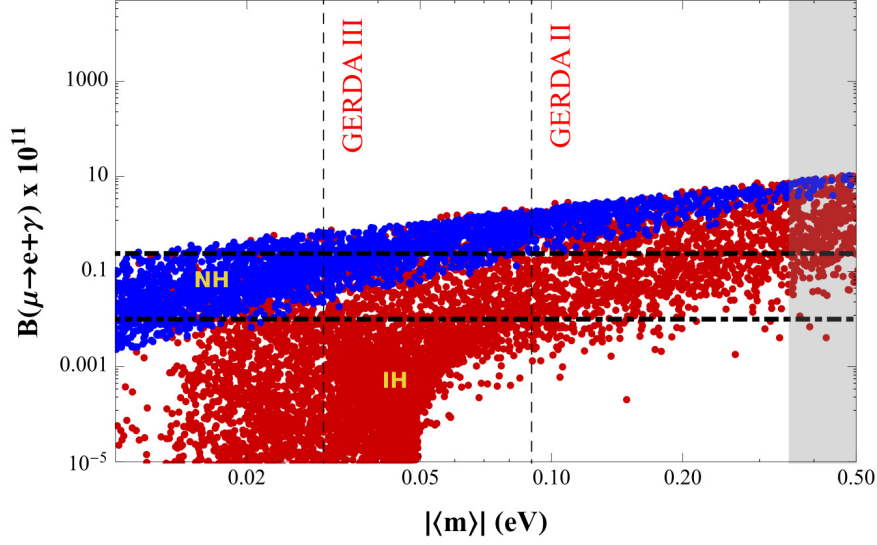


Figure 2. $B(\mu \rightarrow e + \gamma)$ vs $|\langle m \rangle|$ for $M_1 = 100$ GeV and $|M_2 - M_1|/M_1 = 10^{-3}$.

TeV scale type I see-saw mechanism. Indeed, in the simple extension of the Standard Model considered, with the addition of two heavy RH neutrinos N_1 and N_2 at the TeV scale, which behave as a pseudo-Dirac particle, *a sizable (dominant) contribution of N_1 and N_2 to the $(\beta\beta)_{0\nu}$ -decay rate would imply a “large” enhancement of the muon radiative decay rate.* In fact, if $|\langle m \rangle| \cong |\langle m \rangle^N|$, where $\langle m \rangle^N$ is given in eq. (8), it is easy to show that [3]

$$B(\mu \rightarrow e + \gamma) \cong \frac{3\alpha_{\text{em}}}{64\pi} |G(0) - G(M_1^2/M_W^2)|^2 |r|^2 \frac{M_1^2}{M_a^4} \frac{|\langle m \rangle^N|^2}{z^2(f(A))^2}, \quad (14)$$

where $0.5 \lesssim |r| \lesssim 30$ ($0.01 \lesssim |r| \lesssim 5$) for the NH (IH) light neutrino mass spectrum. The analytic relation in eq. (14) is confirmed by the results of the numerical computation reported in figure 2, where it is shown the correlation between the $\mu \rightarrow e + \gamma$ branching ratio and the effective Majorana mass in the case of sizable couplings between the RH (pseudo-Dirac pair) neutrinos and charged leptons. In general, a lower bound on $B(\mu \rightarrow e + \gamma)$ within the MEG experiment sensitivity reach is set for both light neutrino mass hierarchies (normal and inverted) if a positive signal is detected by GERDA, *i.e.* for $|\langle m \rangle| \sim 0.1$ eV.

In conclusion, the observation of $(\beta\beta)_{0\nu}$ -decay in the next generation of experiments, under preparation at present, and of the $\mu \rightarrow e + \gamma$ decay in the MEG experiment, could be the first indirect evidence for the TeV scale type I see-saw mechanism of neutrino mass generation.

References

- [1] P. Minkowski, Phys. Lett. B **67** (1977) 421; M. Gell-Mann, P. Ramond and R. Slansky, *Proceedings of the Supergravity Stony Brook Workshop*, New York 1979, eds. P. Van Nieuwenhuizen and D. Freedman; T. Yanagida, *Proceedings of the Workshop on Unified Theories and Baryon Number in the Universe*, Tsukuba, Japan 1979, eds. A. Sawada and A. Sugamoto; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** (1980) 912; W. Konetschny, W. Kummer, Phys. Lett. **B70** (1977) 433; T. P. Cheng, L. -F. Li, Phys. Rev. **D22**, 2860 (1980); G. Lazarides, Q. Shafi, C. Wetterich, Nucl. Phys. **B181**, 287 (1981); J. Schechter, J. W. F. Valle, Phys. Rev. **D22**, 2227 (1980); R. N. Mohapatra, G. Senjanovic, Phys. Rev. **D23**, 165 (1981).
- [2] A. Ibarra, E. Molinaro and S. T. Petcov, JHEP **1009** (2010) 108 [arXiv:1007.2378 [hep-ph]].
- [3] A. Ibarra, E. Molinaro and S. T. Petcov, Phys. Rev. D **84** (2011) 013005 [arXiv:1103.6217 [hep-ph]].
- [4] A. A. Smolnikov [GERDA Collaboration], arXiv:0812.4194 [nucl-ex].
- [5] J. Adam *et al.* [MEG Collaboration], [arXiv:1107.5547 [hep-ex]].